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Thermomechanical Properties of Selected Space-Related Materials

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14. ABSTRACT

Room-temperature values for nine thermomechanical material properties of 130 space-related materials have been tabulated in this report. These data are essential for analyses to determine material response to pulsed radiation that relate to survivability assessments of space systems based on above- and below-ground nuclear weapons effects experiments. The nine properties tabulated for each of the 130 materials include density, specific heat (constant pressure), specific heat (constant volume), Poisson's ratio, Grüneisen constant, adiabatic sound velocity, Young's modulus, isothermal bulk modulus, and volumetric coefficient of thermal expansion.

Various appropriate elements, oxides, carbides, halides, metallic alloys, semiconductors, optical materials, glasses, plastic and graphites are included in the tabulation. The majority of the materials are high density, low porosity, isotropic and polycrystalline in form.

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Dedication

For Bill Childs; colleague and friend.

Foreword

The analysis of radiation interaction with, and damaging effects to, operational military systems requires a comprehensive database of thermophysical and other properties, covering the diversity of materials to be found in such systems, including spacecraft, launch and reentry vehicles, and their components. Computations of nuclear weapon or directed-energy weapon effects requires specialized knowledge and expertise, together with experience using the appropriate computer codes.

With the cessation of the cold war, efforts addressing the vulnerability, survivability, and hardening of military systems were severely scaled back. Consequently, the personnel who had maintained the associated analytical technologies were reassigned, retired, or discharged. Much knowledge and capability was lost in the process.

The Editors of this report have attempted to partially mitigate such losses by preserving this previously unpublished database of equation-of-state and related materials properties data, together with a tutorial on the derivation of equations for computing the Grüneisen constant. The data presented herein was collected and used by Mr. William H. "Bill" Childs in the analysis of thermal stress-related effects, and was found among his files at The Aerospace Corporation Space Materials Laboratory following his death in September, 1997.

During the period, 1965 through 1992, researchers in The Aerospace Corporation's Laboratory Operations conducted experiments on some 28 underground nuclear tests (UGTs) at Mercury, Nevada. Concurrently with these UGTs, and subsequent to the termination of underground testing in 1992, innumerable experiments were conducted using high-energy pulsed-power facilities at government and contractor laboratories in so-called "above ground tests" (AGTs). Bill Childs' career spanned the entire era of underground testing of space-related materials. His analytical efforts were critical to the support of virtually every nuclear weapon effects experiment conducted by Aerospace, whether underground or above ground, as well as the many "paper" studies related to vulnerability, survivability, and hardening done during that time.

In 1981, Childs published the first volume of his compendium of temperature-dependent thermophysical properties. Volume I* presented tables of data for 112 materials, together with curve fits suitable for computer code input. This was followed in 1986 by the publication of Volume II,** which presented data on an additional 107 materials. These volumes have become industry standards as data reference for radiation effects modeling and analysis. Childs was in the process of preparing a third volume, intended for the presentation of his collection of thermomechanical properties data, but

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* Childs, W. H., "Thermophysical Properties of Selected Space-Related Materials", Vol. I, Aerospace Report No. TOR-0081(6435-02)-01, 20 February, 1981.

** Childs, W. H., "Thermophysical Properties of Selected Space-Related Materials", Vol. II, Aerospace Report No. TOR-0086(6435-02)-01, 15 February, 1986.

this was not completed during his lifetime. With its publication at this time, it is appropriate that this volume be dedicated to its original author.

The reader is cautioned that the information and data contained herein are presented as found among Childs' papers. These are known to be the data personally used by Childs, and informally provided by him to other workers in the field of radiation effects. Only minimal attempts have been made to compare the data in Childs' tables against data that might be found in the listed source materials. However, when comparisons were made, no inconsistencies could be found between Childs' data and those of other workers. In particular, Ho (ref. 88) presents a table of data calculated using a somewhat different method but that, nevertheless, agrees with Child's data to within about 10%.

The text has been edited and organized to comply with Corporation document standards. Corrections have been made where errors were found and some editorial changes have been made for clarity. However, the technical text remains essentially as written by Childs.

Data selection was made on the basis of Childs' judgement, in consultation with others. In particular, Dr. Robert Cooper is known to have given much advice and support to Childs' analytical activities. Cooper's editorial notes and comments on a draft copy of the text were found among Childs' papers and have been incorporated in this present document.

The list of data sources and references has been particularly a concern because Childs left multiple versions, including several pages of handwritten notes citing intended additions to the list of references. Explicit reference citations for the properties data selected by Childs and presented in his database could not be found. In an attempt to somewhat compensate for this lack, we have superficially reviewed the referenced documents to identify content related to the 130 materials in the database, without determining the actual source of data selected and tabulated by Childs. These observations of content have been appended to the materials list given in Section 7. However, the uncertainty of specific data origins remains a caveat to the reader.

Some of the referenced documents are quite obscure and will be difficult to locate using ordinary library services. Accordingly, the editors intend to preserve those reference documents found among Childs' holdings by transferring their possession to the Corporate Archivist of The Aerospace Corporation. Interested readers may obtain access to those reports by contacting the Corporate Archivist.

Symbols and Units

C_B	Bulk wave velocity	(cm/s)
C_L	Longitudinal wave velocity	(cm/s)
C_S	Shear wave velocity	(cm/s)
C_P	Heat capacity at constant pressure	(cal/g-°C)
C_V	Heat capacity at constant volume	(cal/g-°C)
E	Internal Energy	(cal/g)
G_R	Reuss averaged shear modulus	(dynes/cm^2)
G_V	Voigt averaged shear modulus	(dynes/cm^2)
B_H	Hashin averaged shear modulus	(dynes/cm^2)
G_S	Shtrikman averaged shear modulus	(dynes/cm^2)
K	Hashin and Shtrikman averaged bulk modulus	(dynes/cm^2)
K_R	Reuss averaged bulk modulus	(dynes/cm^2)
K_V	Voigt averaged bulk modulus	(dynes/cm^2)
K_A	Adiabatic bulk modulus	(dynes/cm^2)
K_I	Isothermal bulk modulus	(dynes/cm^2)
P	Pressure	(dynes/cm^2)
S	Entropy or degree of disorder	
T	Absolute Temperature	(°K)
V	Volume	(cm^3)
X_A	Adiabatic compressibility	(dynes/cm^2)$^{-1}$
X_I	Isothermal compressibility	(dynes/cm^2)$^{-1}$
Y	Young's modulus of elasticity	(dynes/cm^2)

β	Volumetric coefficient of thermal expansion	(10^{-6}°C^{-1})
γ	Grüneisen constant	
λ	Lamè elastic constant	(dynes/cm^2)
μ	Shear modulus	(dynes/cm^2)
ν	Poisson's ratio	
ρ	Density	(g/cm^3)

Contents

1. Introduction

The thermomechanical material properties tabulated in this report are a consistent set of room-temperature data compiled for 130 space-related materials. These data are essential for analyses to determine material response to pulsed radiation, which relates to survivability assessments based on above and below ground weapons effects experiments. The need for such a compilation has been expressed by analysts on many occasions in connection with DoD, AFSD, AFRL, and DTRA-sponsored programs. The nine properties tabulated for each of the 130 materials include density, specific heat (constant pressure), specific heat (constant volume), Poisson's ratio, Grüneisen constant, adiabatic sound velocity, Young's modulus, isothermal bulk modulus, and volumetric coefficient of thermal expansion. Although the units are admittedly inconsistent, they have been selected for usage without conversion by the majority of users.

Among the 130 materials included in the tabulation are representative elements, oxides, carbides, halides, metallic alloys, semiconductors, optical materials, glasses, plastics, and graphites. The majority of the materials are high density, low porosity, isotropic and polycrystalline in form, unless otherwise stated. However, in a few cases, the materials are not completely characterized.

The tabulated values of material properties have been extracted from the literature without undertaking a complete or thorough search. The selected values represent the results of both experimental measurements and calculations. No attempt was made to validate the data. The bibliography, although not complete, provides the opportunity to consult the original references in most cases.

Whenever possible, experimentally measured isothermal properties were compared with values calculated from adiabatic measurements. The approach in this report was to calculate the Grüneisen constant, first based on an equation derived from thermodynamics relating to the adiabatic state, and second by means of an equation derived from thermodynamics relating to the isothermal state. These values are also compared with the Grüneisen constants that have been determined experimentally. This comparison was extended to provide a test of the consistency of the tabulated properties.

Sections 2, 3, and 4 of this report present the derivation of equations used for calculating the Grüneisen constants. Alternate methods of calculating elastic properties for isotropic materials from the anisotropic single-crystal elastic constants are presented in Section 5.

Section 6 provides the list of reference documents used by Childs as data sources for generating the compendium of material properties presented in Section 8. Section 7 presents an alphabetical list of the 130 space-related materials included in the database, together with citations to the specific data sources, to be found in the list of reference documents, for each material.

2. Methods of Analysis for the Grüneisen Constant

The format for the Compendium of Thermomechanical Properties presented in Section 8 provides for reporting values of the Grüneisen constant obtained using one or more of three distinct methods. For those materials for which no experimental data were available, values of the Grüneisen constant have been calculated using one of the two algorithms developed below.

Method 1 presents experimentally determined values of the Grüneisen constant for materials, when available in the literature.

The second method of calculating the Grüneisen constant uses the relation for isothermal conditions given in Eq. (3.15) of Section 3:

$$\gamma = \frac{\beta K_I}{C_V \rho}, \tag{2.1}$$

where β is the volumetric coefficient of thermal expansion, K_I is the isothermal bulk modulus, C_V is the heat capacity at constant volume, and ρ is the density.

To be consistent throughout this report, the values for the heat capacity at constant volume, C_V, will be calculated from the thermodynamic expression given in Eq. (2.3).

$$C_P - C_V = -T\left(\frac{\partial V}{\partial T}\right)_P^2 \bullet \left(\frac{\partial P}{\partial V}\right)_T \tag{2.2}$$

$$C_V = C_P - \left(\frac{\beta^2 T K_I}{\rho}\right), \tag{2.3}$$

where T is the absolute temperature. This equation applies equally to solids, liquids, and gases. There are many methods of calculating the heat capacity at constant volume, such as those given by Dulong and Petit, Einstein, Drude, Debye, and Born and Karman. It is felt that the above relationship should not introduce any appreciable errors in the calculations.

The isothermal bulk modulus, which is not always available for many materials, can be calculated by other expressions as given in Section 4. The table in Section 4 presents the relationships among five elastic constants: bulk modulus (K), Young's modulus (Y), Poisson's ratio (ν), Lamè constants (λ and μ(shear)). The table is organized to facilitate computation of the remaining three of these parameters when any two of the five are known, for isotropic linear elastic materials.

It would be desirable to calculate the elastic properties for random, macroscopically isotropic aggregates of crystals from the single-crystal anisotropic elastic constants. This is not yet possible, but bounds have been obtained for the aggregate properties from the single-crystal constants (Section 4). These are called the "Voigt" and "Reuss" averages. Voigt averaged the elastic stiffnesses (C_{ij}) over all space, and Reuss averaged the elastic compliances (S_{ij}). [2] These values are considered the least upper bound and the greatest lower bound, respectively, for the aggregate.

The <u>third method</u> of calculating the Grüneisen constant uses the relation for adiabatic conditions given in Eq. (3.22) of Section 3.

$$\gamma = \frac{\beta K_A}{C_P \rho}, \tag{2.4}$$

where K_A is the adiabatic bulk modulus, C_P is the heat capacity at constant pressure, and

$$K_A = \rho C_B{}^2. \tag{2.5}$$

The adiabatic bulk wave speed (C_B) is calculated from shock wave measurements, where the longitudinal, C_L, and the shear, C_S, speeds have been determined. The shear wave is also referred to as the transverse wave. Then the bulk wave speed can be expressed as

$$C_B = \left(C_L{}^2 - \frac{4}{3} C_S{}^2 \right)^{\frac{1}{2}}. \tag{2.6}$$

The adiabatic bulk modulus can also be calculated from the isotropic elastic properties when shock wave measurements are not available. The longitudinal and shear wave speed can be expressed as follows:

$$C_L = \left(\frac{3K_A(1-\upsilon)}{\rho(1+\upsilon)} \right)^{\frac{1}{2}} \ ; \ C_S = \left(\frac{3K_A(1-2\upsilon)}{2\rho(1+\upsilon)} \right)^{\frac{1}{2}}. \tag{2.7}$$

The wave speeds can also be expressed in terms of the Lamè elastic constants.

$$C_L = \left(\frac{\lambda + 2\mu}{\rho} \right)^{\frac{1}{2}} \ ; \ C_S = \left(\frac{\mu}{\rho} \right)^{\frac{1}{2}}. \tag{2.8}$$

The same relationship exists as given in Section 5 by substituting values calculated from C_L and C_S.

$$\upsilon = \frac{C_L{}^2 - 2C_S{}^2}{2\left(C_L{}^2 - C_S{}^2\right)} \tag{2.9}$$

$$Y = \frac{\rho C_S{}^2\left(3C_L{}^2 - 4C_S{}^2\right)}{\left(C_L{}^2 - C_S{}^2\right)} \tag{2.10}$$

$$K_A = \rho\left(C_L{}^2 - \frac{4}{3}C_S{}^2\right) \tag{2.11}$$

3. Derivation of Equations to Calculate the Grüneisen Constant Using Various Experimental Parameters

For most solids, a simple relationship has been shown by Grüneisen to have experimental validity:

$$\gamma = \frac{\text{Volume Coefficient of Thermal Expansion} \times \text{Specific Volume}}{\text{Compressibility} \times \text{Specific Heat (Constant Volume)}}, \tag{3.1}$$

and γ is called the Grüneisen constant.[5] Experimental values of γ for most solids lie between 1.5 and 2.5. A theoretical basis for the Grüneisen constant has been established by Slater in his derivation of the Mie-Grüneisen equation of state:

$$(P - P_0)V = \gamma(E - E_0), \tag{3.2}$$

where the subscripted values of pressure (P) and internal energy (E) are the volume (V) dependent values at zero Kelvin. [6]

A number of expressions relating the Grüneisen constant to various thermoelastic and thermodynamic parameters can be derived from the Mie-Grüneisen equation of state. A simple and straightforward demonstration of their interrelationships, which follows, involves the use of Jacobians. By differentiating Eq. (3.2) while holding volume constant, we obtain:

$$\gamma = V\left(\frac{\partial P}{\partial E}\right)_V \tag{3.3}$$

$$\left(\frac{\partial P}{\partial E}\right)_V = \frac{J(P,V)}{J(E,V)} = \frac{J(P,V)/J(T,V)}{J(E,V)/J(T,V)} = \frac{\left(\frac{\partial P}{\partial T}\right)_V}{\left(\frac{\partial E}{\partial T}\right)_V}. \tag{3.4}$$

The specific heat (constant volume) is defined:

$$C_V = \left(\frac{\partial E}{\partial T}\right)_V = \left(\frac{\partial S}{\partial T}\right)_V. \tag{3.5}$$

Substituting:

$$\gamma = \frac{V}{C_V}\left(\frac{\partial P}{\partial T}\right)_V, \tag{3.6}$$

and using Maxwell's relation:

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V. \tag{3.7}$$

Eq. (3.6) can also be written:

$$\gamma = \frac{V}{C_V}\left(\frac{\partial S}{\partial V}\right)_T. \tag{3.8}$$

But

$$\left(\frac{\partial P}{\partial T}\right)_V = \frac{J(P,V)}{J(T,V)} = \frac{(-)J(V,P)/J(T,P)}{J(V,T)/J(P,T)} = \frac{(-)\left(\frac{\partial V}{\partial T}\right)_P}{\left(\frac{\partial V}{\partial P}\right)_T}, \tag{3.9}$$

so

$$\gamma = \frac{(-)V}{C_V} \bullet \frac{\left(\frac{\partial V}{\partial T}\right)_P}{\left(\frac{\partial V}{\partial P}\right)_T}. \tag{3.10}$$

The volume coefficient of thermal expansion is defined:

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P, \tag{3.11}$$

and the isothermal compressibility is defined:

$$X_I = \frac{(-)1}{V}\left(\frac{\partial V}{\partial P}\right)_T = \frac{1}{K_I}, \tag{3.12}$$

where K_I is the isothermal bulk modulus. Substituting in Eq. (3.10):

$$\gamma = \frac{\beta V}{C_V X_I} = \frac{\beta V K_I}{C_V}. \tag{3.13}$$

Usually the Mie-Grüneisen equation of state, Eq. (3.2), is expressed in terms of the specific volume which is related to the density:

$$V = \frac{1}{\rho}. \tag{3.14}$$

Therefore, Eq. (3.13) becomes

$$\gamma = \frac{\beta}{C_V X_I \rho} = \frac{\beta K_I}{C_V \rho}. \tag{3.15}$$

Using the alternate definition of C_V, Eq. (3.10) can be rewritten:

$$\gamma = \frac{(-)V}{T}\left(\frac{\partial V}{\partial T}\right)_P \bullet \frac{\left(\frac{\partial P}{\partial V}\right)_T}{\left(\frac{\partial S}{\partial T}\right)_V}. \tag{3.16}$$

But

$$\frac{\left(\frac{\partial P}{\partial V}\right)_T}{\left(\frac{\partial S}{\partial T}\right)_V} = \frac{J(P,T)/J(V,T)}{J(S,V)/J(T,V)} = \frac{J(P,S)/J(V,S)}{J(S,P)/J(T,P)} = \frac{\left(\frac{\partial P}{\partial V}\right)_S}{\left(\frac{\partial S}{\partial T}\right)_P}, \tag{3.17}$$

and the specific heat (constant pressure) is defined:

$$C_P = \left(\frac{\partial H}{\partial T}\right)_P = T\left(\frac{\partial S}{\partial T}\right)_P. \tag{3.18}$$

Substituting in the equation above:

$$\gamma = \frac{(-)V}{C_P}\left(\frac{\partial V}{\partial T}\right)_P\left(\frac{\partial P}{\partial V}\right)_S. \tag{3.19}$$

The adiabatic (isoentropic) compressibility and bulk modulus are defined:

$$X_A = (-)\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_S = \frac{1}{K_A}. \tag{3.20}$$

Substituting in Eq. (3.19):

$$\gamma = \frac{\beta V}{C_P X_A} = \frac{\beta V K_A}{C_P} \tag{3.21}$$

$$\gamma = \frac{\beta}{C_P X_A\, \rho} = \frac{\beta K_A}{C_P\, \rho}. \tag{3.22}$$

Equation (3.19) can be rewritten:

$$\gamma = \frac{(-)V^2\beta}{C_P}\left(\frac{\partial P}{\partial V}\right)_S. \tag{3.23}$$

The adiabatic (isoentropic) sound speed is defined:

$$C_B = V\left[(-)\left(\frac{\partial P}{\partial V}\right)_S\right]^{\frac{1}{2}}. \tag{3.24}$$

Substituting in Eq. (3.23):

$$\gamma = \frac{\beta}{C_P} C_B{}^2. \tag{3.25}$$

Several facts are evident from the equations that have been derived. It is evident that Eq. (3.13) is identical to Eq. (3.1), which was the original definition of the Grüneisen constant, γ. It is possible to evaluate γ from several different sets of experimental data:

(1) Using Eq. (7), γ can be obtained from the specific heat (constant volume), density, volumetric thermal expansion, and isothermal compressibility (or bulk modulus).

(2) Using Eq. (10), γ can be obtained from the density, specific heat (constant pressure) volumetric thermal expansion, and adiabatic compressibility (or modulus).

(2) Using Eq. (12), γ can be obtained from the specific heat (constant pressure), volumetric thermal expansion, and adiabatic sound velocity.

4. Equations Linking Five Elastic Constants

	λ	μ	Y	ν	K
λ, μ			$\frac{\mu(3\lambda+2\mu)}{\lambda+\mu}$	$\frac{\lambda}{2(\lambda+\mu)}$	$\frac{3\lambda+2\mu}{3}$
λ, Y		$\frac{(Y-3\lambda)+\sqrt{(Y-3\lambda)^2+8\lambda Y}}{4}$		$\frac{-(Y+\lambda)+\sqrt{(Y+\lambda)^2+8\lambda^2}}{4\lambda}$	$\frac{(3\lambda+Y)+\sqrt{(3\lambda+Y)^2-4\lambda Y}}{6}$
λ, ν		$\frac{\lambda(1-2v)}{2v}$	$\frac{\lambda(1+v)(1-2v)}{v}$		$\frac{\lambda(1+v)}{3v}$
λ, K		$\frac{3(K-\lambda)}{2}$	$\frac{9K(K-\lambda)}{3K-\lambda}$	$\frac{\lambda}{3K-\lambda}$	
μ, Y	$\frac{(2\mu-Y)\mu}{Y-3\mu}$			$\frac{Y-2\mu}{2\mu}$	$\frac{\mu Y}{3(3\mu-Y)}$
μ, ν	$\frac{2\mu v}{(1-2v)}$		$2\mu(1+v)$		$\frac{2\mu(1+v)}{3(1-2v)}$
μ, K	$\frac{3K-2\mu}{3}$		$\frac{9K\mu}{3K+\mu}$	$\frac{1}{2}\left[\frac{3K-2\mu}{3K+\mu}\right]$	
Y, ν	$\frac{vY}{(1+v)(1-2v)}$	$\frac{Y}{2(1+v)}$			$\frac{Y}{3(1-2v)}$
Y, K	$\frac{3K(3K-Y)}{9K-Y}$	$\frac{3YK}{9K-Y}$		$\frac{1}{2}\left[\frac{3K-Y}{3K}\right]$	
ν, K	$\frac{3Kv}{1+v}$	$\frac{3K(1-2v)}{2(1+v)}$	$3K(1-2v)$		

5. Development of Equations to Calculate Aggregate Material Properties from Those of Single Crystals

Editor's Note: The text of this section presents the author's unabridged development and rationale for the calculation of aggregate properties from those of single crystals—it has been reproduced with only minor formatting changes from Childs' original draft. It is recognized that the uninitiated reader will likely have some difficulty in following this development because of the lack of rigor and other lapses. However, it is hoped that the inclusion of this section will provide useful insight into Childs' approach. The interested reader may find additional insights by referring to other treatments of this subject to be found in the literature. (cf. Ref. 88.)

The Voigt and Reuss bulk modulus averages are given by

$$K_V = (A + 2B)/3 \quad \text{and} \quad K_R = 1/(3a + 6b), \text{ respectively,} \tag{5.1}$$

and the shear moduli of rigidity averages are

$$G_V = (A - B + 3C)/5 \quad \text{and} \quad G_R = 5/(4a - 4b + 3c). \tag{5.2}$$

The constants A, B, C and a, b, c are related to the elastic stiffnesses and compliances by the relations

$$\begin{aligned} 3A &= C_{11} + C_{22} + C_{33} & \qquad 3a &= S_{11} + S_{22} + S_{33} \\ 3B &= C_{23} + C_{31} + C_{12} & \qquad 3b &= S_{23} + S_{31} + S_{12} \\ 3C &= C_{44} + C_{55} + C_{66} & \qquad 3c &= S_{44} + S_{55} + S_{66} \end{aligned} \tag{5.3}$$

Again, knowing any two of the elastic properties, the rest can be calculated from the isotropic elastic relations given in Section 4. No distinction is made between adiabatic and isothermal elastic properties, which should not differ by more than a few percent.

The constants, A, B, and C have been further reduced for six specific crystalline structures as follows [7]:

Crystalline Structure	Definition of Constants A, B, & C	
Cubic	$A = C_{11}$ $B = C_{12}$ $C = C_{44}$	(5.4)
Hexagonal and Trigonal	$A = 1/3\ (2C_{11} + C_{33})$ $B = 1/3\ (2C_{13} + C_{12})$ $C = 1/3\ (2C_{44} + C_{66})$	(5.5)
	where $C_{66} = 1/2(C_{11} - C_{12})$	(5.6)
Tetragonal	$A = 1/3\ (2C_{11} + C_{33})$ $B = 1/3\ (2C_{13} + C_{12})$ $C = 1/3\ (2C_{44} + C_{66})$	(5.7)
Orthorhombic and Monoclinic	$A = 1/3\ (C_{11} + C_{22} + C_{33})$ $B = 1/3\ (C_{13} + C_{23} + C_{12})$ $C = 1/3\ (C_{44} + C_{55} + C_{66})$	(5.8)

Improvements have been made for the upper and lower bounds for cubic crystals and are known as the "Hashin" and "Shtrikman" averages. [2] For single-phase aggregate of a cubic material, the bulk modulus, K, is given unambiguously by

$$K = \frac{1}{3}\left(C_{11} + 2C_{12}\right) \tag{5.9}$$

and the modulus of rigidity is bounded by

$$G_H = G_1 + 3\left(\frac{5}{G_2 - G_1} - 4\sigma_1\right)^{-1} \tag{5.10}$$

and

$$G_S = G_2 + 2\left(\frac{5}{G_1 - G_2} - 6\sigma_2\right)^{-1}, \tag{5.11}$$

where

$$G_1 = \frac{1}{2}(C_{11} - C_{12}) \tag{5.12}$$

$$G_2 = C_{44} \tag{5.13}$$

$$\sigma_1 = -\frac{3(K + 2G_1)}{5G_1(3K + 4G_1)} \tag{5.14}$$

$$\sigma_2 = -\frac{3(K + 2G_2)}{5G_2(3K + 4G_2)}. \tag{5.15}$$

G_H is termed the Hashin rigidity, and G_S is the smaller Shtrikman rigidity.

In general, crystals are anisotropic with respect to their elastic properties. That is, the values of these moduli differ with direction in the crystal. A measure of the anisotropy of a cubic crystal is given by the anisotropy factor ($\tilde{A}$) and is defined as

$$\tilde{A} = \frac{2C_{44}}{(C_{11} - C_{12})} \tag{5.16}$$

For those crystals with $\tilde{A} > 1$, such as germanium and silicon, Young's modulus has its maximum value along the <100> direction and the minimum value along the <111> direction. For crystals with $\tilde{A} < 1$, such as sodium chloride, Young's modulus has its maximum value along the <111> direction and its minimum along the <100> direction. The variation in elastic properties with direction may be as great as 30%.

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7. List of Materials with their Associated Data References

1	Aluminum	1, 2, 5, 8, 22, 25, 27, 31, 34, 42, 47, 51, 56, 57, 58, 62, 68, 69, 70, 85
2	Aluminum 2024	24, 25, 51, 54, 76
3	Aluminum Oxide (Poly)	2, 24, 38, 47, 48 51, 62, 88
4	Aluminum Oxide (S.C.)	2, 8, 24, 39, 47, 51, 72
5	Aluminum 6061-T6	24, 25, 31, 50, 51, 76
6	Antimony	7, 11, 25
7	ATJ Graphite	24, 25, 34, 36, 47, 62, 76
8	Barium	30
9	Beryllium	1, 2, 24, 25, 31, 34, 41, 42, 44, 47, 51, 54, 62, 76, 85
10	Beryllium Oxide	2, 24, 38, 41, 47, 51, 62
11	Bismuth	2, 8, 11, 25, 34, 42, 47
12	Boron	34, 45
13	Boron Carbide	24, 25
14	Brass 70/30	8, 22, 25, 31, 34, 42, 51, 54, 58, 62
15	Cadmium	1, 2, 5, 11, 25, 34, 42, 47, 51, 62
16	Cadmium Sulphide (S.C.)	2, 8, 39, 40, 47, 51, 77
17	Calcium	30
18	Calcium Carbonate (Calcite)	2, 8, 24, 39, 47, 77
19	Carbon Phenolic	22, 25, 36, 54
20	Cerium	46, 62
21	Chromium	2, 11, 25, 34, 42, 51, 54, 58, 62
22	Chromium Oxide	38
23	Cobalt	1, 2, 6, 11, 25, 31, 34, 42, 47, 51, 54, 62, 64
24	Cobalt Oxide	38, 51, 85
25	Copper	1, 2, 6, 8, 11, 22, 24, 25, 27, 31, 34, 42, 47, 50, 51, 54, 56, 57, 58, 62, 64, 70, 88
26	Corning 7740 (PYREX)	1, 8, 40, 51
27	Corning 7940 (Fused Silica)	1, 8, 14, 39, 40, 47, 48, 51, 62, 64, 72
28	Corning 7971 (ULE)	
29	Corning 9606 (PYROCERAM)	
30	Dysprosium	2, 46, 47, 62
31	Erbium	2, 46, 47, 62
32	Europium	46, 62
33	Gadolinium	2, 46, 47, 62, 77
34	Gallium Antimonide (S.C.)	2, 8, 39, 47, 77, 88
35	Gallium Arsenide	8, 21, 39, 40, 47, 51
36	Germanium (S.C.)	1, 2, 8, 9, 21, 24, 39, 40, 44, 47, 51, 56, 57, 64, 72, 88
37	Gold	1, 2, 5,11, 25, 31, 34, 42, 47, 51, 54, 62, 64
38	Hafnium	2, 25, 31, 45, 47, 54

39	Hafnium Carbide	45, 47
40	Holmium	46, 47, 62
41	Indium	2, 34, 42, 44, 47, 51, 62
42	Indium Antimonide (S.C.)	2, 8, 39, 40, 47, 57, 77
43	INVAR 36/74	47, 58, 70
44	Iridium	2, 31, 47
45	Iron	1, 2, 5, 6, 8, 11, 24, 25, 34, 42, 47, 51, 54, 58, 62, 85
46	Iron (Ni 10)	51
47	Iron (Ni 18)	51
48	Iron (Ni 26)	51
49	Iron Oxide	34, 38
50	IRTRAN-1 (MgF2)	2, 38, 39, 48, 72, 73
51	IRTRAN-2 (ZnS)	2, 34, 66, 72, 77, 88
52	IRTRAN-3 (CaF2)	2, 5, 34, 39, 48, 72
53	IRTRAN-4 (ZnSe)	2, 34, 72, 77, 88
54	IRTRAN-5 (MgO)	2, 34, 39, 48, 62, 64, 72
55	IRTRAN-6 (CdTe)	2, 8, 39, 51, 72, 77, 88
56	Kapton	35, 70
57	KEL-F	7, 39, 51
58	Kovar	51, 70
59	Lanthanum	46, 62
60	Lead	1, 2, 5, 8, 11, 24, 25, 31, 34, 42, 47, 51, 54, 58, 62, 85
61	Lead Sulphide (S.C.)	2, 5, 8, 39, 47, 55, 77
62	Lithium Flouride (S.C.)	2, 8, 34, 39, 40, 47, 64, 77, 88
63	Lithium Niobate (S.C.)	2, 40, 47, 77
64	Lucite	1, 2, 25, 34, 35, 50, 67
65	Leutetium	40, 46, 47, 62
66	Magnesium	1, 2, 25, 31, 34, 42, 47, 51, 54, 58, 62, 85
67	Magnesium Oxide	2, 8, 38, 39, 40, 47, 48, 62, 64, 88
68	Molybdenum	2, 5, 11, 31, 34, 42, 45, 47, 51, 54, 58, 62, 70, 88
69	Mylar	25, 35, 51
70	Neodymium	46, 47, 62, 76
71	Nickel	1, 2, 5, 6, 11, 25, 31, 34, 42, 47, 51, 54, 58, 62
72	Nickel Oxide	38
73	Niobium	2, 6, 24, 25, 34, 42, 45, 47, 54, 58
74	Niobium Carbide	45, 47
75	Nylon 6	1, 4, 7, 17, 25, 35, 51, 67
76	OTWR (Quartz phenolic)	7, 22, 25, 54
77	Palladium	2, 5, 6, 25, 31, 34, 42, 47, 51, 54
78	Platinum	1, 2, 5, 6, 8, 25, 31, 34, 42, 47, 51, 54, 62, 88
79	Plutonium (alpha)	46
80	POCO Graphite (AXF)	16, 26
81	Polyethylene (high density)	1, 8, 17, 24, 25, 34, 35, 40, 54, 62
82	Polystyrene	1, 4, 17, 25, 31, 34, 35, 40, 51, 62
83	Polyvinylchloride	17, 35
84	Potassium Bromide (S.C.)	1, 2, 5, 8, 34, 39, 47, 77, 88

85	Potassium Chloride (S.C.)	1, 2, 5, 8, 34, 39, 47, 64, 77, 88
86	Potassium Iodide (S.C.)	2, 8, 34, 39, 47, 77, 88
87	Praseodymium	46, 47, 62
88	Pyrolytic Graphite	16, 26, 47
89	Quartz Phenolic	25, 50, 54
90	Quartz (S.C.)	2, 8, 34, 39, 40, 47, 48, 51, 54, 64, 76, 88
91	Rhenium	2, 44, 47
92	Rhodium	31, 34, 42, 47, 62
93	Scandium	46
94	Silicon	2, 8, 9, 21, 39, 40, 47, 51, 56, 57, 72, 77, 88
95	Silicon Carbide	9, 25, 62
96	Silver	1, 2, 5, 6, 8, 11, 25, 31, 34, 42, 47, 51, 54, 57, 58, 62, 64, 70
97	Silver Chloride (S.C.)	1, 2, 5, 8, 39, 47, 77
98	Sodium Chloride (S.C.)	2, 4, 5, 8, 24, 34, 47, 64, 72, 77, 88
99	Stainless Steel 304L	24, 25
100	Strontium	30
101	Tantalum	2, 5, 24, 25, 31, 34, 42, 45, 47, 51, 54, 58, 62
102	Tantalum Carbide	2, 24, 45, 47
103	Teflon	4, 8, 25, 35, 51, 68, 69, 70
104	Terbium	46, 47, 62, 76
105	Thallium Bromide (S.C.)	2, 34, 39
106	Thallium Bromide-Chloride	2, 34, 39
107	Thallium Bromide-Iodide	2, 39
108	Thallium Chloride (S.C.)	2, 39
109	Thorium	2, 11, 24, 25, 31, 34, 42, 46, 54
110	Thorium Dioxide	2, 38, 47
111	Thulium	46
112	Tin	1, 2, 8, 11, 24, 25, 31, 34, 42, 47, 51, 53, 58, 62, 85
113	Tin Oxide	38, 55
114	Titanium	1, 2, 11, 24, 25, 31, 34, 42, 45, 47, 49, 51, 54, 58, 62, 76, 85
115	Titanium Carbide	2, 24, 45, 47, 62
116	Titanium Dioxide	8, 38, 39, 47, 48, 49
117	Tungsten	1, 2, 5, 6, 11, 24, 31, 34, 45, 47, 51, 54, 58, 62, 88
118	Tungsten Carbide	24, 25, 45, 58
119	Uranium	2, 24, 25, 31, 46, 47, 54
120	Uranium Oxide	2, 38
121	Vanadium	2, 11, 25, 31, 34, 45, 54, 58, 62
122	VYCOR	
123	Ytterbium	46, 47, 62
124	Yttrium	2, 46, 47
125	Yttrium Aluminate (YAG, S.C.)	40, 47
126	Zinc	1, 2, 5, 8, 11, 25, 34, 42, 47, 51, 54, 58, 62, 85
127	Zinc Oxide	2, 38, 47, 50

128	Zirconium	2, 24, 25, 31, 34, 42, 45, 47, 51
129	Zirconium Carbide	2, 24, 45, 47
130	Zirconium Dioxide	38, 47, 62

8. Compendium of Thermomechanical Property Data for 130 Materials

ALUMINUM

DENSITY (g/cm)	POISSON'S RATIO
2.71	0.345

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5375	69.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2160	0.2064

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.706	0.752

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.350	2.225	2.236

ALUMINUM 2024

DENSITY (g/cm)	POISSON'S RATIO
2.79	0.330

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5209	67.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2200	0.2117

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.724	0.710

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.000	1.990	1.939

ALUMINUM OXIDE (POLY)

DENSITY
(g/cm)

4.0

POISSON'S RATIO

0.232

SOUND VELOCITY

(cm/microsec)

0.7933

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

16.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1870	0.1858

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
4.060	2.500

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.327	1.327

ALUMINUM OXIDE (S.C.)

<u>DENSITY</u> (g/cm)	<u>POISSON'S RATIO</u>
3.97	0.181

<u>SOUND VELOCITY</u> (cm/microsec)	<u>VOL. COEFF. THERMAL EXPANSION</u>, (10^{-6} °C^{-1})
0.7776	17.4

<u>HEAT CAPACITY</u>, (cal/ g –C)

(Cp)	(Cv)
0.1850	0.1837

(Dynes/cm * 10^{12})

<u>YOUNGS MODULUS</u>	<u>BULK MODULUS</u>
4.600	2.401

<u>GRÜNEISEN CONSTANT</u>

<u>METHOD 1</u>	<u>METHOD 2</u>	<u>METHOD 3</u>
—	1.359	1.369

ALUMINUM 6061 —T6

DENSITY (g/cm)	POISSON'S RATIO
2.7	0.331

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5266	68.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2130	0.2041

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.738	0.728

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.130	2.119	2.150

ANTIMONY

DENSITY (g/cm)	POISSON'S RATIO
6.7	0.088

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2167	33.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0483	0.0479

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.778	0.315

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.801	0.769	0.775

ATJ GRAPHITE

DENSITY (g/cm)	POISSON'S RATIO
1.77	0.270

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1864	5.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1750	0.1750

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.079	0.057

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.027	0.027	0.025

BARIUM

DENSITY
(g/cm)

3.5

POISSON'S RATIO

0.229

SOUND VELOCITY

(cm/microsec)

0.1575

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

62.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0437	0.0430

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.141	0.087

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.841	0.854

BERYLLIUM

DENSITY (g/cm)	POISSON'S RATIO
1.85	0.028

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.7931	33.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.4360	0.4310

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.095	1.147

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.170	1.155	1.152

BERYLLIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
3.03	0.224

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.8437	19.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2460	0.2442

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.570	2.157

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.314	1.324

BISMUTH

DENSITY (g/cm)	POISSON'S RATIO
9.8	0.254

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1864	40.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0293	0.0289

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.503	0.340

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.139	1.155

BORON

DENSITY (g/cm)	POISSON'S RATIO
2.5	0.139

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.9231	14.1

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.2643	0.2631

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
4.613	2.130

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.086	1.091

BORON CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
2.45	0.172

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.9269	14.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2500	0.2487

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
4.249	2.157

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.183	1.218

BRASS 70/30

DENSITY (g/cm)	POISSON'S RATIO
8.52	0.350

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3622	59.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0905	0.0872

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.006	1.118

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.069	2.148

CADMIUM

DENSITY (g/cm)	POISSON'S RATIO
8.65	0.319

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2571	92.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0553	0.0513

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.621	0.572

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.645	2.854

CADMIUM SULPHIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.82	0.373

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3566	15.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0880	0.0878

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.468	0.614

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.518	0.520

CALCIUM

DENSITY (g/cm)	POISSON'S RATIO
1.54	0.263

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3317	67.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1568	0.1533

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.241	0.170

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.124	1.150

CALCIUM CARBONATE (CALCITE)

DENSITY (g/cm)	POISSON'S RATIO
2.71	0.387

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6918	17.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2030	0.2020

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.883	1.297

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.980	0.985

CARBON PHENOLIC

DENSITY (g/cm)	POISSON'S RATIO
1.43	0.342

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3347	39.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2085	0.2073

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.151	0.159

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.510	0.510	0.509

CERIUM

DENSITY (g/cm)	POISSON'S RATIO
6.67	0.248

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1742	15.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0490	0.0489

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.300	0.198

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.232	0.228

CHROMIUM

DENSITY (g/cm) 7.16	**POISSON'S RATIO** 0.210
SOUND VELOCITY (cm/microsec) 0.4730	**VOL. COEFF. THERMAL EXPANSION**, (10^{-6} °C^{-1}) 22.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1075	0.1067

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.790	1.602

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.080	1.129	1.138

CHROMIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
5.25	—

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
—	26.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1650	—

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
—	—

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.400	—	—

COBALT

DENSITY (g/cm)	POISSON'S RATIO
8.67	0.320

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4630	39.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1010	0.0987

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.040	1.830

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.970	1.989	2.004

COBALT OXIDE

DENSITY (g/cm)	POISSON'S RATIO
5.7	—

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
—	36.6

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.1750	—

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
—	—

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.600	—	—

COPPER

DENSITY (g/cm)

8.94

POISSON'S RATIO

0.343

SOUND VELOCITY (cm/microsec)

0.3927

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

49.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0910	0.0883

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.298	1.378

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.000	2.009	2.069

CORNING 7740 (PYREX®)

DENSITY (g/cm)	POISSON'S RATIO
2.23	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3879	9.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1840	0.1839

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.628	0.349

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.193	0.201

CORNING 7940 (FUSED SILICA)

DENSITY (g/cm)	POISSON'S RATIO
2.2	0.160

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4071	1.7

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.1800	0.1800

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.725	0.366

GRÜNEISEN CONSTANT		
METHOD 1	METHOD 2	METHOD 3
—	0.036	0.036

CORNING 7971 (ULE®)

DENSITY
(g/cm)

2.2

POISSON'S RATIO

0.170

SOUND VELOCITY

(cm/microsec)

0.3958

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

0.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1780	0.1780

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.676	0.345

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.002	0.002

CORNING 9606 (PYROCERAM®)

DENSITY (g/cm)	POISSON'S RATIO
2.6	0.240

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5410	1.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1720	0.1720

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.187	0.761

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.049	0.049

DYSPROSIUM

DENSITY (g/cm)	POISSON'S RATIO
8.54	0.243

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0,2280	28.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0414	0.0411

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.631	0.410

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.861	0.801`

ERBIUM

DENSITY (g/cm)	POISSON'S RATIO
9.05	0.238

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2298	28.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0401	0.0398

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.733	0.465

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.891	0.873

EUROPIUM

DENSITY (g/cm)

5.25

POISSON'S RATIO

0.286

SOUND VELOCITY (cm/microsec)

0.1581

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

75.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0421	0.411

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.147	0.131

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.064	1.090

GADOLINIUM

DENSITY
(g/cm)
7.9

POISSON'S RATIO
0.259

SOUND VELOCITY
(cm/microsec)
0.2212

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
6.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0550	0.0550

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.562	0.389

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.128	0.128

GALLIUM ANTIMONIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.62	0.244

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3195	20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0602	0.599

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.880	0.574

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.839	0.844

GALLIUM ARSENIDE

DENSITY (g/cm)	POISSON'S RATIO
5.31	0.334

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3873	20.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0803	0.0799

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.791	0.797

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.911	0.916

GERMANIUM (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.32	0.279

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3824	17.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0769	0.0766

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.025	0.778

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.782	0.785

GOLD

DENSITY (g/cm)	POISSON'S RATIO
19.24	0.420

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} $^{\circ}C^{-1}$)
0.3056	42.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0331	0.0320

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.812	1.692

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.970	2.879	2.808

HAFNIUM

DENSITY (g/cm)	POISSON'S RATIO
13.3	0.284

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2984	18.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0345	0.0343

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.535	1.184

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.040	1.110	1.117

HAFNIUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
12.6	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3940	15.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0460	0.0458

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.521	1.956

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.210	1.217

HOLMIUM

DENSITY (g/cm)	POISSON'S RATIO
8.78	0.255

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2386	29.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0393	0.0390

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.667	0.458

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.018	0.941

INDIUM

DENSITY (g/cm)	POISSON'S RATIO
7.3	0.452

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2231	97.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0550	0.0516

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.105	0.363

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.240	2.106	2.243

INDIUM ANTIMONIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.78	0.259

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2740	14.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0497	0.0496

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.626	0.433

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.531	0.531

INVAR® 36/74

DENSITY (g/cm)	POISSON'S RATIO
8.05	0.259

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3514	2.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1230	0.1230

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.440	0.994

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.065	0.065

IRIDIUM

DENSITY (g/cm)	POISSON'S RATIO
22.5	0.190

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3724	19.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0308	0.0304

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
5.798	3.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.077	2.100

IRON

DENSITY (g/cm)

7.86

POISSON'S RATIO

0.293

SOUND VELOCITY (cm/microsec)

0.4595

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

35.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1070	0.1051

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.114	1.698

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.690	1.670	1.740

IRON (Ni 10)

DENSITY (g/cm)

7.88

POISSON'S RATIO

0.285

SOUND VELOCITY (cm/microsec)

0.4457

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

28.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1130	0.1119

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
2.022	1.565

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.185	1.196

IRON (Ni 18)

DENSITY (g/cm)

7.97

POISSON'S RATIO

0.306

SOUND VELOCITY (cm/microsec)

0.4403

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

34.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1150	0.1134

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.797	1.543

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.370	1.387

IRON (Ni 26)

DENSITY (g/cm)	POISSON'S RATIO
7.97	0.328

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4368	39.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1190	0.1169

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.566	1.521

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.521	1.550

IRON OXIDE

DENSITY (g/cm)	POISSON'S RATIO
4.98	0.318

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6243	29.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1560	0.1535

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.121	1.941

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.779	1.808

IRTRAN® —1 (MgF_2)

DENSITY (g/cm)	POISSON'S RATIO
3.18	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5620	31.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2440	0.2418

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.145	1.004

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.965	0.974

IRTRAN® —2 (ZnS)

DENSITY (g/cm)	POISSON'S RATIO
4.09	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4552	20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1130	0.1124

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.966	0.847

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.907	0.912

IRTRAN® —3 (CaF2)

DENSITY
(g/cm)
3.18

POISSON'S RATIO
0.310

SOUND VELOCITY
(cm/microsec)
0.5218

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
57.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2170	0.2106

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.987	0.866

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.727	1.780

IRTRAN® —4 (ZnSe)

DENSITY (g/cm)	POISSON'S RATIO
5.27	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3440	22.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0800	0.0796

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.711	0.624

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.785	0.789

IRTRAN® —5 (MgO)

DENSITY (g/cm)

3.77

POISSON'S RATIO

0.170

SOUND VELOCITY (cm/microsec)

0.6675

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

31.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2220	0.2188

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.326	1.680

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.521	1.543

IRTRAN® —6 (CdTe)

DENSITY (g/cm)	POISSON'S RATIO
5.85	0.250

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2042	15.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0560	0.0559

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.366	0.244

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.283	0.283

KAPTON®

DENSITY (g/cm)	POISSON'S RATIO
1.42	0.433

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2327	85.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2390	0.2362

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.031	0.077

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.461`	0.467

KEL —F®

DENSITY (g/cm)	POISSON'S RATIO
2.11	0.378

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1496	228.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2200	0.2117

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.035	0.047

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.554	0.576

KOVAR®

DENSITY (g/cm)	POISSON'S RATIO
8.34	0.341

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4038	18.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1050	0.1046

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.297	1.360

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.668	0.670

LANTHANUM

DENSITY (g/cm)	POISSON'S RATIO
6.17	0.288

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2048	15.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0470	0.0469

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.359	0.243

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.335	0.315

LEAD

DENSITY (g/cm)	**POISSON'S RATIO**
11.3	0.440

SOUND VELOCITY (cm/microsec)	**VOL. COEFF. THERMAL EXPANSION**, (10^{-6} °C^{-1})
0.2002	86.9

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.0305	0.0283

YOUNGS MODULUS (Dynes/cm * 10^{12})	**BULK MODULUS** (Dynes/cm * 10^{12})
0.161	0.458

GRÜNEISEN CONSTANT

METHOD 1	**METHOD 2**	**METHOD 3**
2.780	2.729	2.972

LEAD SULPHIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.5	0.470

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2880	72.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0390	0.0359

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.113	0.622

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	3.659	3.971

LITHIUM FLOURIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
2.64	0.214

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4870	103.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3860	0.3683

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.059	0.617

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.513	1.562

LITHIUM NIOBATE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.7	0.255

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4999	33.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1515	0.1495

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.728	1.174

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.313	1.330

LUCITE®

DENSITY (g/cm)

1.19

POISSON'S RATIO

0.323

SOUND VELOCITY (cm/microsec)

0.2177

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

223.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3100	0.2932

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.060	0.056

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.815	0.862

LEUTETIUM

DENSITY
(g/cm)
9.84

POISSON'S RATIO
0.233

SOUND VELOCITY
(cm/microsec)
0.2313

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
24.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0470	0.0468

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.843	0.526

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.677	0.681

MAGNESIUM

DENSITY (g/cm)	POISSON'S RATIO
1.74	0.291

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4444	74.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2444	0.2362

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.447	0.356

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.460	1.445	1.548

MAGNESIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
3.77	0.182

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6780	31.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2220	0.2190

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.100	1.625

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.559	1.482

MOLYBDENUM

DENSITY (g/cm)	POISSON'S RATIO
10.2	0.293

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5033	14.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0592	0.0588

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.248	2.612

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.520	1.473	1.498

MYLAR®

DENSITY (g/cm)	POISSON'S RATIO
1.39	0.370

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2200	171.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2260	0.2166

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.055	0.063

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.875	0.855

NEODYMIUM

DENSITY (g/cm)	POISSON'S RATIO
7.0	0.306

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2157	20.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0490	0.0489

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.379	0.325

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.470	0.470

NICKEL

DENSITY (g/cm)	POISSON'S RATIO
8.9	0.306

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4523	40.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1070	0.1046

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.198	1.876

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.830	1.842	1.942

NICKEL OXIDE

DENSITY (g/cm)	POISSON'S RATIO
6.8	—

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
—	30.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1420	—

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
—	—

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.500	—	—

NIOBIUM

DENSITY (g/cm)	POISSON'S RATIO
8.57	0.397

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4460	21.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0633	0.0626

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.049	1.703

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.680	1.645	1.661

NIOBIUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
7.63	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4981	17.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0880	0.0875

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.407	1.893

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.152	1.159

NYLON 6

DENSITY (g/cm)	POISSON'S RATIO
1.11	0.398

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2380	257.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.3710	0.3437

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.039	0.064

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.020	0.938	1.036

OTWR (QUARTZ PHENOLIC)

DENSITY
(g/cm)

1.66

POISSON'S RATIO

0.260

SOUND VELOCITY
(cm/microsec)

0.3170

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

12.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.4160	0.4159

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.240	0.167

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.073	0.073

PALLADIUM

DENSITY (g/cm)	POISSON'S RATIO
11.4	0.335

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3829	35.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0580	0.0567

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.653	1.670

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.180	2.145	2.192

PLATINUM

DENSITY (g/cm)	POISSON'S RATIO
21.5	0.390

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3538	26.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0317	0.0311

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.670	2.530

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.400	2.501	2.396

PLUTONIUM (ALPHA)

DENSITY (g/cm)	POISSON'S RATIO
19.74	0.150

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1611	141.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0320	0.0287

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.993	0.467

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.733	2.783

POCO GRAPHITE (AXF)

DENSITY (g/cm)	POISSON'S RATIO
1.84	0.280

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2380	11.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2110	0.2110

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.138	0.104

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.071	0.071

POLYETHYLENE (HIGH DENSITY)

DENSITY
(g/cm)
0.95

POISSON'S RATIO
0.385

SOUND VELOCITY
(cm/microsec)
0.2249

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
385.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.5300	0.4780

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.032	0.047

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.950	0.878	0.949

POLYSTYRENE

DENSITY (g/cm)	POISSON'S RATIO
1.05	0.379

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1976	220.0

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.3200	0.3063

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS
0.030	0.042

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.700	0.642	0.680

POLYVINYLCHLORIDE

DENSITY (g/cm)	POISSON'S RATIO
1.4	0.380

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1933	207.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2400	0.2286

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.038	0.052

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.770	0.808

POTASSIUM BROMIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
2.75	0.245

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2461	116.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1040	0.0982

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.255	0.167

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.615	1.715

POTASSIUM CHLORIDE (S.C.)

DENSITY
(g/cm)

1.98

POISSON'S RATIO

0.216

SOUND VELOCITY

(cm/microsec)

0.2963

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

110.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1636	0.1560

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.297	0.174

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.411	1.479

POTASSIUM IODIDE (S.C.)

DENSITY
(g/cm)
3.13

POISSON'S RATIO
0.251

SOUND VELOCITY
(cm/microsec)
0.1936

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
128.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0790	0.0746

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.175	0.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.451	1.532

PRASEODYMIUM

DENSITY (g/cm)	POISSON'S RATIO
6.77	0.305

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2114	16.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0460	0.0459

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.352	0.299

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.376	0.372

PYROLYTIC GRAPHITE

DENSITY (g/cm)	POISSON'S RATIO
2.24	0.150

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3319	1.7

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.1650	0.1650

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.518	0.247

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.023	0.026	0.026

QUARTZ PHENOLIC

DENSITY
(g/cm)

1.78

POISSON'S RATIO

0.254

SOUND VELOCITY

(cm/microsec)

0.3156

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

25.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2276	0.2272

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.262	0.177

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.289	0.261	0.262

QUARTZ (S.C.)

DENSITY
(g/cm)
2.65

POISSON'S RATIO
0.140

SOUND VELOCITY
(cm/microsec)
0.3770

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
40.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1770	0.1753

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.700	0.370

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.780	0.783	0.776

RHENIUM

DENSITY (g/cm)	POISSON'S RATIO
21.1	0.288

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4118	18.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0332	0.0328

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
4.541	3.577

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.271	2.299

RHODIUM

DENSITY (g/cm) 12.45	**POISSON'S RATIO** 0.328
SOUND VELOCITY (cm/microsec) 0.4778	**VOL. COEFF. THERMAL EXPANSION**, (10^{-6} °C^{-1}) 24.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0590	0.0580

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
2.940	2.842

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.270	2.284	2.323

SCANDIUM

DENSITY (g/cm)	POISSON'S RATIO
2.99	0.269

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4296	30.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1370	0.1358

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.793	0.572

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.969	1.014

SILICON

DENSITY (g/cm)	POISSON'S RATIO
2.33	0.212

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6545	7.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1700	0.1698

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.690	0.979

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.475	0.466

SILICON CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
3.12	0.165

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.7999	10.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1650	0.1645

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.862	1.921

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.945	0.912

SILVER

DENSITY (g/cm)	POISSON'S RATIO
10.5	0.367

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3176	56.8

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0564	0.0541

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.827	1.036

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.550	2.428	2.474

SILVER CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
5.56	0.409

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2811	90.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0850	0.0804

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.240	0.442

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.000	2.127

SODIUM CHLORIDE (S.C.)

DENSITY
(g/cm)
2.14

POISSON'S RATIO
0.252

SOUND VELOCITY
(cm/microsec)
0.3410

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
121.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2040	0.1917

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.375	0.252

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.648	1.779

STAINLESS STEEL 304L

DENSITY (g/cm)

7.9

POISSON'S RATIO

0.280

SOUND VELOCITY (cm/microsec)

0.4496

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

44.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1160	0.1131

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.153	1.660

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.845	1.968

STRONTIUM

DENSITY (g/cm)	POISSON'S RATIO
2.6	0.297

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2118	67.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0686	0.0671

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.142	0.117

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.055	1.078

TANTALUM

DENSITY (g/cm)	POISSON'S RATIO
16.6	0.342

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3388	18.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0330	0.0327

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.857	1.963

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.690	1.571	1.634

TANTALUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
14.4	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3315	16.8

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.0455	0.0453

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
2.848	1.582

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.970	0.974

TEFLON®

DENSITY (g/cm)	POISSON'S RATIO
2.18	0.433

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1289	308.0

HEAT CAPACITY, (cal/ g –C)	
(Cp)	(Cv)
0.2410	0.2302

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.014	0.035

GRÜNEISEN CONSTANT		
METHOD 1	METHOD 2	METHOD 3
0.480	0.508	0.509

TERBIUM

DENSITY
(g/cm)

8.23

POISSON'S RATIO

0.261

SOUND VELOCITY
(cm/microsec)

0.2199

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

28.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0437	0.0434

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
0.575	0.400

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.748	0.758

THALLIUM BROMIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.56	0.321

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1724	158.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0450	0.0397

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.241	0.225

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.494	2.830

THALLIUM BROMIDE —CHLORIDE

DENSITY (g/cm)	POISSON'S RATIO
7.19	0.333

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1700	150.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0480	0.0429

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.242	0.228

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.159	2.649

THALLIUM BROMIDE —IODIDE

DENSITY (g/cm)	POISSON'S RATIO
7.37	0.333

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1635	174.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0365	0.0307

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.199	0.198

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	3.046	3.638

THALLIUM CHLORIDE (S.C.)

DENSITY (g/cm)	POISSON'S RATIO
7.0	0.322

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1835	159.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0520	0.0459

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.252	0.236

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	2.461	2.790

THORIUM

DENSITY (g/cm)	POISSON'S RATIO
11.7	0.302

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2327	33.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0283	0.0279

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.751	0.632

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.514	1.534

THORIUM DIOXIDE

DENSITY (g/cm)	POISSON'S RATIO
9.87	0.170

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2651	23.2

HEAT CAPACITY, (cal/ g –C) (Cp)	(Cv)
0.0560	0.0557

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
1.373	0.693

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.696	0.699

THULIUM

DENSITY (g/cm)	POISSON'S RATIO
9.31	0.235

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2223	36.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0382	0.0377

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.755	0.475

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.113	1.163

TIN

DENSITY (g/cm)	POISSON'S RATIO
7.29	0.340

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.2703	66.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0545	0.0525

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.450	0.469

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.110	2.128	1.944

TIN OXIDE

DENSITY (g/cm)	POISSON'S RATIO
6.95	—

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
—	11.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0830	—

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
—	—

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.600	—	—

TITANIUM

DENSITY
(g/cm)

4.6

POISSON'S RATIO

0.340

SOUND VELOCITY

(cm/microsec)

0.4919

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

25.3

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1240	0.1229

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.060	1.104

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.180	1.180	1.181

TITANIUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
4.9	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5985	19.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1340	0.1331

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
3.159	1.755

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.227	1.235

TITANIUM DIOXIDE

DENSITY
(g/cm)

4.0

POISSON'S RATIO

0.271

SOUND VELOCITY

(cm/microsec)

0.6663

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

22.6

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1690	0.1674

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.440	1.776

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.419	1.433

TUNGSTEN

DENSITY (g/cm)	POISSON'S RATIO
19.3	0.280

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4014	13.5

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0318	0.0316

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
4.110	3.110

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.540	1.635	1.646

TUNGSTEN CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
15.7	0.220

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4508	11.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0510	0.0508

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
5.344	3.190

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.057	1.061

URANIUM

DENSITY (g/cm)

19.1

POISSON'S RATIO

0.197

SOUND VELOCITY (cm/microsec)

0.2431

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

41.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0276	0.0269

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.054	1.129

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.060	2.144	2.204

URANIUM OXIDE

DENSITY (g/cm)	POISSON'S RATIO
10.3	0.310

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3985	28.2

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0649	0.0640

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.814	1.591

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.649	1.626

VANADIUM

DENSITY (g/cm)	POISSON'S RATIO
6.0	0.365

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5072	23.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1043	0.1033

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.276	1.580

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
1.290	1.379	1.426

VYCOR®

DENSITY (g/cm)	POISSON'S RATIO
2.18	0.190

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4125	2.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.2000	0.2000

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.690	0.371

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.049	0.049

YTTERBIUM

DENSITY (g/cm)	POISSON'S RATIO
6.97	0.284

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.1446	75.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0346	0.0338

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.178	0.138

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.089	1.053

YTTRIUM

DENSITY (g/cm)	POISSON'S RATIO
4.46	0.255

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3274	33.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0680	0.0671

YOUNGS MODULUS (Dynes/cm * 10^{12})	BULK MODULUS (Dynes/cm * 10^{12})
0.663	0.469

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.277	1.270

YTTRIUM ALUMINATE (YAG®, S.C.)

DENSITY (g/cm)	POISSON'S RATIO
4.55	0.249

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.6374	26.7

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1542	0.1521

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
2.780	1.849

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.681	1.705

ZINC

DENSITY
(g/cm)

6.92

POISSON'S RATIO

0.249

SOUND VELOCITY

(cm/microsec)

0.3128

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})

90.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0929	0.0870

YOUNGS MODULUS	BULK MODULUS
(Dynes/cm * 10^{12})	
1.045	0.694

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
2.450	2.288	2.504

ZINC OXIDE

DENSITY (g/cm)	POISSON'S RATIO
5.6	0.354

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.5020	12.9

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1180	0.1177

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.235	1.411

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.658	0.660

ZIRCONIUM

DENSITY
(g/cm)
6.5

POISSON'S RATIO
0.332

SOUND VELOCITY
(cm/microsec)
0.3747

VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
17.1

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0652	0.0649

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
0.951	0.892

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
0.870	0.880	0.864

ZIRCONIUM CARBIDE

DENSITY (g/cm)	POISSON'S RATIO
6.4	0.200

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.3460	16.0

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.0900	0.0898

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.379	0.766

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	0.509	0.510

ZIRCONIUM DIOXIDE

DENSITY (g/cm)	POISSON'S RATIO
5.7	0.270

SOUND VELOCITY (cm/microsec)	VOL. COEFF. THERMAL EXPANSION, (10^{-6} °C^{-1})
0.4428	26.4

HEAT CAPACITY, (cal/ g –C)

(Cp)	(Cv)
0.1090	0.1079

(Dynes/cm * 10^{12})

YOUNGS MODULUS	BULK MODULUS
1.687	1.222

GRÜNEISEN CONSTANT

METHOD 1	METHOD 2	METHOD 3
—	1.135	1.254

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Laboratory Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual organizations:

Electronics and Photonics Laboratory: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Space Materials Laboratory: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

Space Science Applications Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; infrared surveillance, imaging, remote sensing, and hyperspectral imaging; effects of solar activity, magnetic storms and nuclear explosions on the Earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation, design fabrication and test; environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes.

Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

Office of Spectral Applications: Multispectral and hyperspectral sensor development; data analysis and algorithm development; applications of multispectral and hyperspectral imagery to defense, civil space, commercial, and environmental missions.

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